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Spatial and temporal variations of precipitation in Haihe River Basin, China: six decades of measurements

Zhonggen Wang,[1] Yuzhou Luo,[1,2]* Changming Liu,[1] Jun Xia[1] and Minghua Zhang[2]
[1] *Key Laboratory of Water Cycle & Related Land Surface Processes, Institute of Geographical Science and Natural Resources Research, Chinese Academy of Science, Beijing 100101, China*
[2] *Department of Land, Air and Water Resources, University of California, Davis, CA 95616, USA*

Abstract:

This study aims to determine temporal trends and spatial distribution of the annual and monthly precipitation in the Haihe River Basin, China, during 1951–2008. A significant decreasing trend was observed for the annual precipitation, mainly attributed to the abrupt decrease in the flood-season precipitation (June–September) around the year of 1979. No significant trend was revealed for precipitation within Period I of 1951–1979 and Period II of 1980–2008. Results of this study indicated that the relative contributions of the flood-season precipitation decreased temporally with time and spatially with elevation. This study also identified a potential movement of storm centers from east to west portions of the basin. In addition, analysis on the precipitation anomalies also suggested a redistribution of the non-flood season precipitation over the study area. Compared with the west portion of the basin, generally, the east received relatively more precipitation during the non-flood season, while similar trend of precipitation redistribution was not observed in the flood season.

KEY WORDS Haihe River Basin; Mann-Kendall test; precipitation; trends; variability

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INTRODUCTION

Climate change and human activity have caused an increasing shortage of water resources in many regions of the world (Vorosmarty *et al*., 2000). Numerous studies have been carried out to characterize the trend and variability of climate change in various geographic areas. Most of those studies were conducted by analyzing climate and hydrologic elements such as precipitation, air temperature, soil moisture, and surface runoff. Precipitation is considered one of the most important driving forces for the variability and availability on surface runoff and other water resources. Abrupt decline in precipitation within the last century has been identified in many regions (Partal and Kahya, 2006; Smadi and Zghoul, 2006).

Some river basins suffer serious eco-environmental problems due to the declining trend and uneven distribution of precipitation. The Haihe River Basin (HRB) of northern China is one such place that faces serious problem of water shortages. Enclosing Beijing, the capital city of China, and other metropolitan areas, the HRB is the political, economic, and cultural center of China. Due to the large population, rapid economic growth, and limited water availability in the region, the water resources per capita is only about 250–300 m^3/ year, 1/7 of the national average of China and 1/24 of the global average (Domagalski *et al*., 2001; Xia *et al*., 2006). Eco-environmental degradations have been caused by insufficient surface water and over-exploitation of groundwater in this area (Li *et al*., 2007).

In the HRB, water resource projects have been developed to control floods and provide water supply for agricultural, industrial, and domestic uses. More than 1900 reservoirs have been built in the basin, with a total storage of 31·6 billion m^3 (Guo and Liu, 2004). Due to the lack of comprehensive analysis on the variations of precipitation in time and space, systematical management of the reservoirs is not available, resulting in inefficient utilization of water resources in the basin. Significant declines on precipitation and surface runoff have been reported by other researchers (Yang and Tian, 2009). However, most of those studies focused on trend estimation and time series analysis for either short period or limited coverage of the entire HRB. Basin-wide analysis on the spatial distribution and temporal pattern of precipitation in this area is not available in the literature. In this study, monthly and annual precipitation measurements during 1951–2008 for 43 weather stations were analyzed in detail to obtain reliable estimates in characterizing the trend and distribution of precipitation in the HRB. The objectives of this study are (1) to characterize the precipitation change in the study area by identifying its general trend and distribution; (2) to analyze the seasonality of precipitation and its changes over time and space; and (3) to determine the dynamics on the storm centers over years. The results of this study were anticipated to provide useful guidance for water resource planning and management in the HRB.

* Correspondence to: Yuzhou Luo, Department of Land, Air and Water Resources, University of California, Davis, CA 95616, USA.
E-mail: yzluo@ucdavis.edu

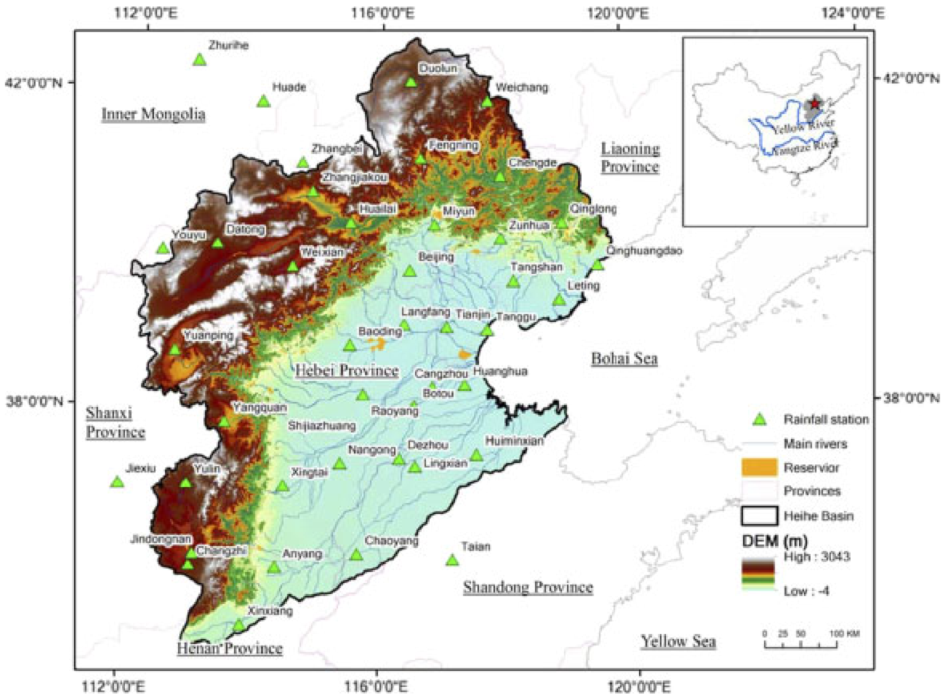

Figure 1. Location of the Haihe River Basin and weather stations

METHODS AND MATERIALS

Study area

The HRB covers 318 200 km^2 in northern China, consisting of mountains and plateaus in the north and west, and the North China Plain in the eastern and southern parts (Figure 1). The basin is located between 35 and 43°N latitude and 112 and 120 °E longitude and is bounded by the Bohai Sea to the east, the Yellow River to the south, the Yunzhong and Taiyue Mountains to the west, and the Mongolian Plateau to the north. All rivers in the basin originate from Yunzhong and Taiyue Mountains and flow eastward and drain to the Bohai Sea via multiple river outlets. The basin is mainly located in Hebei Province and also covers parts of the Provinces of Liaoning, Inner Mongolia, Shanxi, Henan, and Shandong. The basin accounts for only 3·3% of China's total land area but supports 10% of total population and 15% of total Gross Domestic Product (GDP) of China in 2007 (Yang, 2003). With rapid population growth and economic development, the combined problems of water shortage and water contamination significantly constrain the sustainable development in this area (Feng and Cheng, 2001; Xia and Chen, 2001; Yang and Zehnder, 2001).

The study area belongs to the semi-humid climate in the monsoon region of the East Asia warm temperate zone (Edmonds, 1998; Domagalski *et al*., 2001), characterized by hot and wet summers and cold and dry winters. Average temperatures in the basin are between −4·9 and 15·0 °C. Annual precipitation ranges from 359 to 848 mm, majority of which is contributed by the flood season of June to September. Snow accounts for the majority of winter precipitation in the basin. However, snow generally melts away and disappears in 2 or 3 weeks (Yu *et al*., 2010).

Data source

The monitoring network used in this study included 43 evenly distributed weather stations in the study area (Figure 1 and Table I). The network was assumed to represent regional hydro-climatic conditions (Wang *et al*., 2008). Most of the stations have continuous meteorological observations since 1951. Daily precipitation data during 1951–2008 was retrieved from China Meteorological Data Sharing Service System (CMA, 2009). Monthly and annual averages of precipitation were then calculated from the daily measurements and used in the data analysis of this study.

Data analysis

Descriptive statistics was first employed to characterize the monthly and annual precipitation for individual weather stations in the HRB. Missing data were observed for some weather stations during early years of the study period. For a given year, therefore, annual precipitation was only calculated for weather stations with valid measurements for all months during the corresponding year. In another word, if a weather station included missing records for any month during a year, this station was excluded for annual precipitation calculation for that year. The relative magnitudes of monthly precipitation were obtained as the percentages of the precipitation in the corresponding month over the annual total. The sequential version of the Mann–Kendall test (Mann, 1945), or the Mann–Kendall trend test, and linear regression analysis were conducted to determine the abrupt change and temporal trend of the precipitation in the study area.

Table I. Information of weather stations in this study

Station ID[a]	Station name	Latitude	Longitude	Elevation (m)
53276	Zhurihe	42·40	112·90	1150·8
53391	Huade	41·90	114·00	1482·7
53399	Zhangbei	41·15	114·70	1393·3
53478	Youyu	40·00	112·45	1345·8
53487	Datong	40·10	113·33	1067·2
53593	Weixian	39·83	114·57	909·5
53673	Yuanping	38·73	112·72	828·2
53698	Shijiazhuang	38·03	114·42	81·0
53782	Yangquan	37·85	113·55	741·9
53787	Yulin	37·07	112·98	1041·4
53798	Xingtai	37·07	114·50	77·3
53863	Jiexiu	37·03	111·92	743·9
53882	Changzhi	36·05	113·07	991·8
53887	Jindongnan	36·20	113·12	926·5
53898	Anyang	36·05	114·40	62·9
53986	Xinxiang	35·32	113·88	73·2
54208	Duolun	42·18	116·47	1245·4
54308	Fengning	41·22	116·63	661·2
54311	Weichang	41·93	117·75	842·8
54401	Zhangjiakou	40·78	114·88	724·2
54405	Huailai	40·40	115·50	536·8
54416	Miyun	40·38	116·87	71·8
54423	Chengde	40·98	117·95	385·9
54429	Zunhua	40·20	117·95	54·9
54436	Qinglong	40·40	118·95	227·5
54449	Qinghuangdao	39·85	119·52	2·4
54511	Beijing	39·80	116·47	31·3
54518	Langfang	39·12	116·38	9·0
54527	Tianjin	39·08	117·07	2·5
54534	Tangshan	39·67	118·15	27·8
54539	Leting	39·43	118·88	10·5
54602	Baoding	38·85	115·52	17·2
54606	Raoyang	38·23	115·73	19·0
54616	Cangzhou	38·33	116·83	9·6
54618	Botou	38·08	116·55	13·2
54623	Tanggu	39·05	117·72	4·8
54624	Huanghua	38·37	117·35	6·6
54705	Nangong	37·37	115·38	27·4
54714	Dezhou	37·43	116·32	21·2
54715	Lingxian	37·33	116·57	18·6
54725	Huiminxian	37·48	117·53	11·7
54808	Chaoyang	36·23	115·67	37·8
54827	Taian	36·17	117·15	128·8

[a] Station ID is a unique code assigned to each station by China Meteorological Administration (2009).

Preliminary data analysis indicated that more than half of the annual precipitation was observed during the 2 months of July and August. Therefore, storm centers were determined by locating the weather stations with maximum total precipitation for July and August in each year. The storm center in this study was defined with respect to the availability and utilization of water resources. The identified storm center represented the location with maximum observed summer precipitation, which may be significantly associated with local water supplies to agricultural and industrial water demands. To capture the potential spatial pattern of storm center movement, we divided the basin into east and west portions by 116 °E longitude.

Precipitation anomalies were calculated at each station and each year, as the difference in annual precipitation between a station and the basin-wide average of a given year normalized by the corresponding basin-wide standard deviation. Precipitation anomalies represent the relative magnitude of precipitation at each station over the study area. By de-trending the annual variations on precipitation, the changes in anomalies reflect the re-distribution pattern of precipitation in the study area. All statistical analyses were conducted in MathWorks MATLAB R2010.

Spatial interpolation was conducted in this study only to visually display the relative magnitude of precipitation in the monitoring network and associated spatial variability. Interpolation of precipitation data was implemented using inverse distance weighted method provided in ESRI ArcGIS 9·3. The discussion and comparison of technologies in interpolating precipitation are beyond the research focus of this article and thus not presented here.

RESULTS

General characteristics

Figure 2 shows the average annual precipitation in the HRB during 1957–2008 with spatial variability as positive/negative one standard deviation among weather stations. The average annual precipitation over the study period is 535·7 mm, with a coefficient of variation (CV) of 0·18 among years. Compared to annual variation, high spatial variability of annual precipitation among weather stations was observed, as indicated by a CV of 0·34 averaged for the all study years. There was a significant decreasing trend over the study period ($p < 0.05$) for annual precipitation, which decreased by 102 mm (or about 20% of the long-term average of annual precipitation) during the study period of 28 years. Further data analysis indicated that the significant decreasing trend was mainly attributed by the difference in annual precipitation between the years of 1951–1979 (Period I)

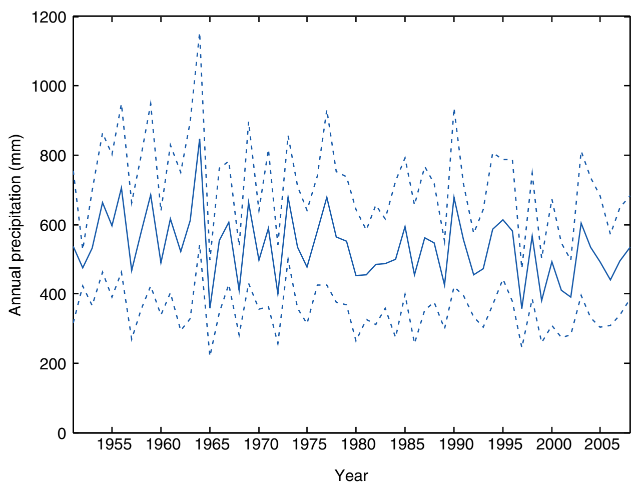

Figure 2. Basin-wide annual precipitation in the Haihe River Basin during 1951–2008. Dotted lines indicate the range of annual precipitation over weather stations within one standard deviation

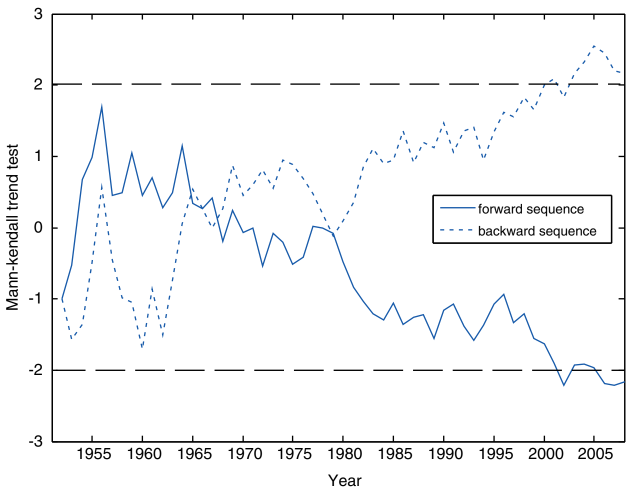

Figure 3. Sequential Mann–Kendall test for annual runoff with forward-trend (solid line) and backward-trend (dotted line) in the Haihe River Basin. Dashed horizontal lines represent critical values corresponding to the 95% con?dence interval

and 1980–2008 (Period II). The average annual precipitation during Period I was 567·9 mm, while that for Period II was 503·5 mm. However, within each period, no significant temporal trend was observed ($p =$ 0·836 and 0·749 for Periods I and II, respectively). The change in precipitation between the two periods was also confirmed by results of sequential Mann–Kendall test (Figure 3). Based on the relative magnitudes of the upward and downward sequences, the abrupt change point was observed around year 1979.

Figure 4 shows the spatial distribution of annual precipitation in the HRB during the study period and during the two periods of 1951–1979 and 1980–2008. There is a general decreasing trend in precipitation from east to west or from the coastline to the mountainous area. The largest precipitation was observed in the lower portion of Luanhe River watershed, northwest to Beijing, while dry areas were identified for the mountainous areas of Taihang Mountains on the west of the study area. Significant negative correlation was found between precipitation and station elevation ($r = -0{\cdot}633$, $p < 0{\cdot}001$), confirming the decreasing trend of precipitation from coastline to mountains. Although basin-wide precipitation decreased significantly between the two periods of 1951–1979 and 1980–2008, spatial pattern of precipitation distribution did not change much during the two periods.

Seasonality

Basin-wide annual precipitation was mainly (77%) contributed during the summer months of June–September, especially in July and August. These 2 months accounted for 54% of total annual rainfall (40–60% varies over weather stations). Further investigation also indicated that the decreasing trend in annual precipitation during the study period was caused by the significantly decreased monthly precipitation in July and August ($p < 0{\cdot}05$). As basin-wide average, monthly precipitation decreased by 36·2 and 59·5 mm, respectively, in July and August. However, the decreasing trends were not significant for other months. Some months, such as May and June, even showed a slight increasing trend of precipitation. The decreases in summer precipitation changed the seasonality of precipitation in the HRB. During 1951–2008, percentage contributions of precipitation by July and August to annual total value were decreased (Figure 5). For example, August contributed 26% to annual precipitation during the years of

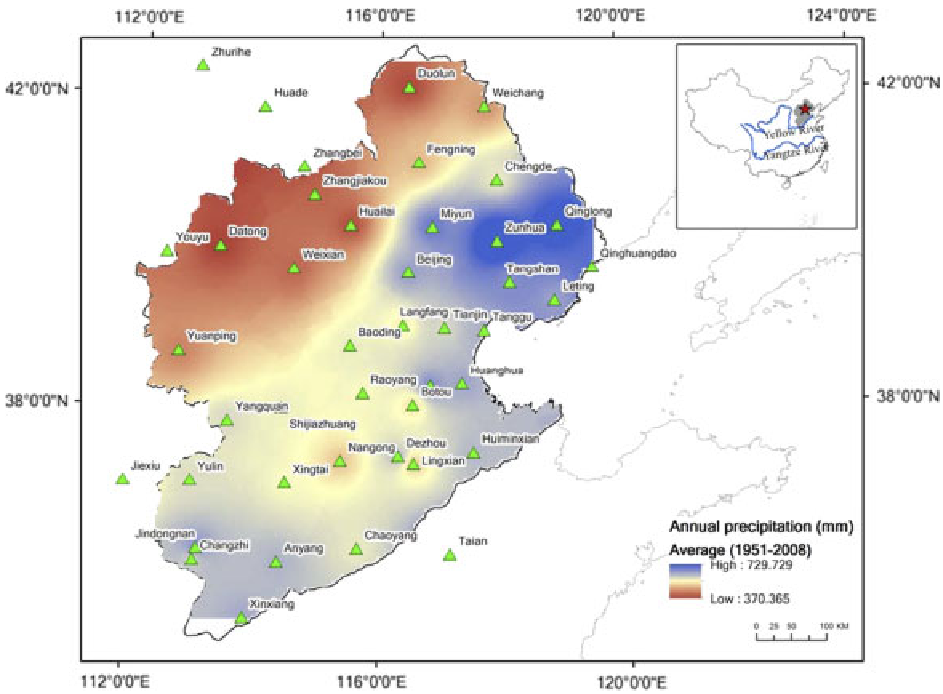

Figure 4. Average of annual precipitation in the Haihe River Basin during 1951–2008

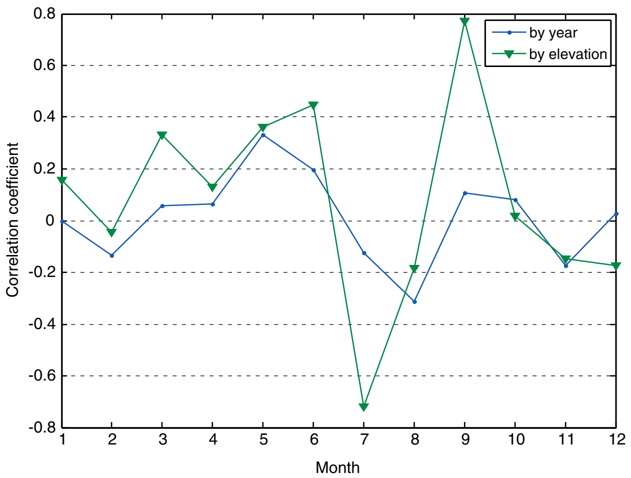

Figure 5. Correlations between percentage contribution of monthly precipitation with year and station elevation in the Haihe River Basin. Critical values are ±0·25 and ±0·30, respectively, at significance level of 0·05

1951–1979, while this value decreased to 23% during 1980–2008 ($p = 0{\cdot}049$ in paired t-test). Consequently, the relative contribution of precipitation by other months increased, especially those during spring and fall. In spite of the fact that annual precipitation kept decreasing in the HRB during the study period, results of this study also confirmed a temporal re-distribution pattern of precipitation from summer months to spring and fall.

Similar change in precipitation seasonality was also observed over weather stations with different elevations (Figure 5). Results of spatial correlation analysis between relative contribution of monthly precipitation and the station elevation indicated that percentage contributions of summer rainfall to total annual rainfall was higher in the basin floor compared with those in the mountainous area. With the increase in elevation, the relative contribution of precipitation by summer months decreased, while the contributions from spring and fall months increased correspondingly. It is very interesting to identify this similarity in both spatial and temporal scale with regard to the relative contribution of summer rainfall given decreased total annual rainfall. Results of this study revealed that when annual precipitation decreased, either with global climate change or with elevated location, monthly rainfall would not simply decrease accordingly, but be redistributed to smooth the seasonality.

Movement of storm centers

In this study, the storm center was defined as the weather stations with highest total precipitation of July and August for each year. As discussed before, 2 months of July and August accounted for about half of the annual precipitation in the HRB. Therefore, summation of July and August precipitation would reasonably capture the spatial distribution of storms in the surrounding area of the weather station. As shown in Figure 4, storm centers were generally located along the line between Qinglong (113·07 °E, 36·05 °N) and Changzhi (118·95 °E, 40·40 °N). For 49 of 58 years, storm centers were found in a band area with width of ±100 km (Figure 6).

For further analysis of storm center movement, in this study, we defined 116 °E longitude as the divider for the east and west portion of the HRB. The two portions have comparable areas within the basin. For 76% of the years (44 of 58) in the study period, storm centers were observed in the east portion of the basin. However, a potential movement trend of storm center from east to west was observed. During Period I of 1951–1979, only

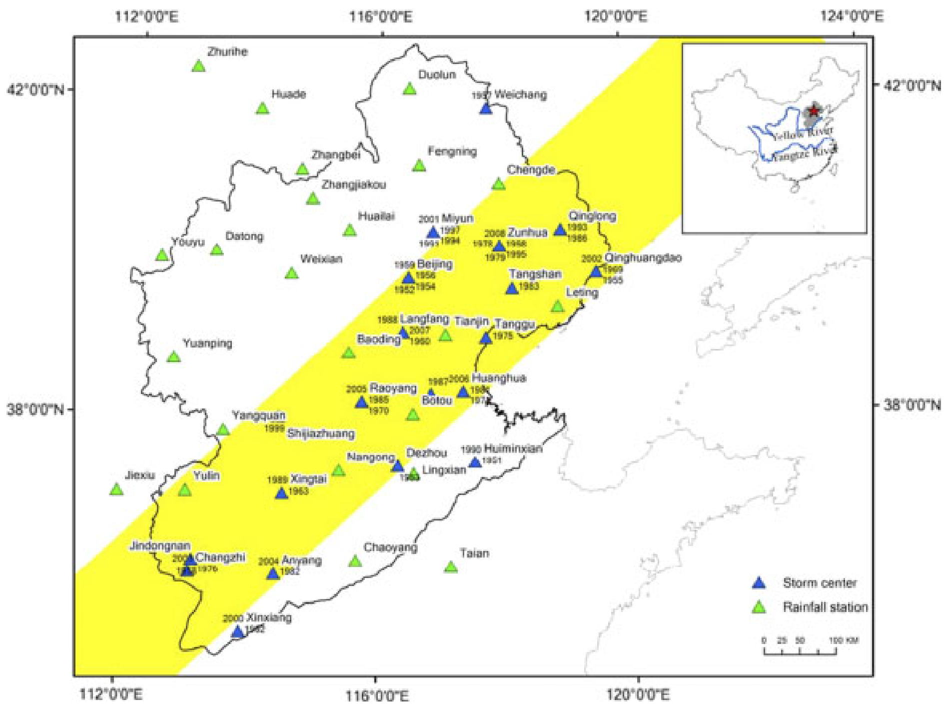

Figure 6. Storm centers (for total precipitation of July and August of each year) in the Haihe River Basin during 1951 through 2008

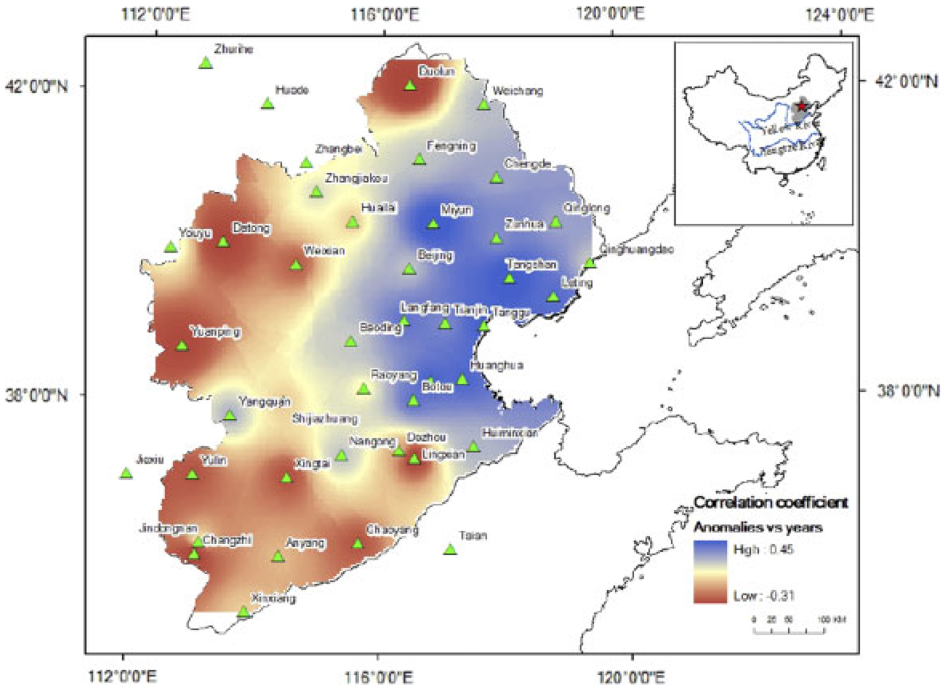

Figure 7. Correlation coefficients between precipitation anomalies of the non-flood season and years during 1951–2008 over the Haihe River Basin. Critical values are ±0·25 for significance level of 0·05

for 3 years, the storm centers were located in west portion of the basin, while this number increased to 11 for Period II of 1980–2008.

Spatial variability on precipitation distribution and trend

Annual precipitation in weather stations shared the same temporal variation of the basin-wide averages. No significant trends were observed for annual precipitation within either Period I (1951–1979) or II (1980–2008). However, all weather stations showed lower mean value of annual precipitation for Period II compared with I. Significant difference ($p < 0{\cdot}05$) in annual precipitation between the two periods was only confirmed at eight weather stations based on paired *t*-tests. For the non-flood season, 24 weather stations showed a larger mean value of precipitation in Period II relative to I, although none of them were statistically significant. Significant higher precipitation in Period I relative to Period I was observed at 12 weather stations during the flood season and at 17 weather stations during the months of July and August. Similar to the basin-wide average, therefore, the difference in annual precipitation at individual weather stations between the two periods was also mainly contributed by the precipitation during the flood season.

Analysis on the temporal trend of precipitation anomalies over weather stations reflected the spatial pattern of precipitation redistribution in the study area. For the flood-season precipitation anomalies and annual total precipitation anomalies, there were no significant temporal trends identified. For the non-flood seasons, however, precipitation anomalies showed significant increasing or decreasing trend over the study period for 10 weather stations. Significant increasing trend of the non-flood season precipitation anomalies was observed for east regions of the HRB, especially in the areas around the Bohai Sea (Figure 7). For the west portion of the study area, precipitation anomalies during the non-flood season showed a general decreasing trend throughout the study years. This finding suggested that the relative contribution of the non-flood season precipitation in east areas increased, even as the absolute values might not change significantly during the study years.

DISCUSSION AND CONCLUSION

The rapid growth of population and economy in the HRB imposes a clear and urgent challenge to water resource sustainability in the region. Similar to other developing regions in the world, crisis in water resources is getting worse due to the increasing demand by economic development and more restrictive regulations on groundwater exploitation. Improvement in the management and utilization of precipitation is the key to protect the environmental quality while sustainablizing the economic development of the region. Understanding the temporal and spatial variations on precipitation will be the very important first step for the efficient water management in the study area.

The long-term annual precipitation over the HRB was 535·7 mm based on the measurements of 1951–2008. Abrupt decrease in the flood-season precipitation was observed around the year of 1979. Since the flood season accounted for 77% of annual precipitation, the abrupt decrease resulted in a significant decrease in annual precipitation during Period II of 1980–2008 compared with Period I of 1951–1979. Consequently, the percentage contribution of the flood-season precipitation in the annual precipitation kept decreasing during the study period. Abrupt decrease in precipitation during late 1970s and middle 1980s was also observed over other regions of China, such as the upper Yellow River Basin (Zhao *et al.*, 2007).

The storm center was identified as the weather station with highest precipitation during the flood season over the study area for each year. This study showed that storm centers were generally located along the line between the weather station of Qinglong (113·07 °E, 36·05 °N) and Changzhi (118·95 °E, 40·40 °N), generally parallel to the coastline of the Pacific Ocean in northern China. In addition, most of the storm centers were located on the weather stations in the plain area of basin floor and associated with low elevations. This also confirmed the significantly negative spatial correlation between annual precipitation and elevation in the basin. Since the major cities and agricultural areas were also located in the basin floor, results of this study suggest that characterization of the variations on precipitation may help improve the management and utilization of water resources in the study area. There was a potential moving trend of storm centers from the east to the west portion of the basin during the study period. This was indicated by the fact that only for 3 years the storm centers were located in west portion of the basin during 1951–1979, while for 11 years during 1980–2008. One of the evidences of storm-center movement is that flow discharge to the reservoirs in the northwestern mountainous area decreased drastically in recent years. For example, the water in the Miyun Reservoir, the main raw water source for Beijing's domestic water supply, has decreased due to continuous drought since 1999, dropping by at least 40% of its previous storage (Liu *et al.*, 2008; Ma *et al.*, 2010). Discovery of the movement of storm centers was anticipated to provide useful information for watershed management planning. In addition to the proposed water diversion by the 'South to North Water Transfer Project', water conservation projects are required to alleviate the water crisis in Beijing and the nearby cities. One of the projects is to convert paddy field to dry farming land over the upper reaches of the reservoirs. At the same time, management system for water saving should be established for industry and public service sectors.

Annual precipitation at weather stations shared the same temporal pattern on the basin-wide annual precipitation, i.e. higher precipitation was observed for Period II compared with I. However, spatial variability was observed based on the trend analysis on the precipitation anomalies during the non-flood season over the weather stations. In the east portion of the basin, especially the areas around the Bohai Sea, a significantly positive trend was revealed for precipitation anomalies during the non-flood season. This indicated that, even though there was a decreasing trend in the annual precipitation, the relative contribution of precipitation during the non-flood season has been increasing in the east portion of the basin. Very important management implications could be generated from this finding, especially for the agricultural production areas. At first, with decreased summer precipitation, the risk of flooding would be significantly reduced in the basin floor. In addition, the changes in precipitation seasonality provide opportunity for the utilization of precipitation and flood to relieve the spring drought in the HRB. With reduced flooding risks in the summer months, more water from precipitation and flood could be collected to increase the water supply for economic and ecological systems. For instance, winter wheat is one of the most important crops in the HRB, which requires intensive irrigation during spring and early summer (Du *et al.*, 2010; Yang *et al.*, 2010). Previous survey results showed that there were 270–300 mm water deficit for the production of winter wheat in the study area, mainly during March–May. Therefore, grain production in the region could be benefited by appropriately adapted management practices for increased precipitation in the non-flood season.

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